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Accidental actions values and combinations for key-elements checking

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Abstract. In the case of accidental design situations, if accidental actions can be identified, one of the possible design strategies is checking the key element. This strategy minimizes the possibility of local failure and subsequent progressive collapse. The paper considers accidental action combinations and values of identified accidental loads according the various codes. The combination of actions for accidental design situation for checking of the "key-element" resistance was proposed. In addition, the values of the combination factors for variable loads and partial factors for permanent loads in accordance with required reliability class RC for structural element and values of accidental loads was proposed.
Keywords: accidental design situation, accidental action, key-element, load combination, robustness.

1 Introduction

Most of the structural codes [1–4] provides a description of principles and application rules for the design of structural systems subjected to accidental action, including impact forces, actions due to internal explosions and due to local failure [5].

According to EN1991-1-7 [3] two groups of strategies are proposed in order to assess accidental design situations: those based on identified accidental actions and those based on limiting the extent of localized failure.

In the first group, it is proposed to design the structure to have sufficient minimum robustness, to prevent or reduce the effect of accidental action or to directly design the structural system to sustain the action.

The second group of strategies is based on limiting the extent of localized failure, either by increasing redundancy of structure or designing "key elements" to sustain notional accidental actions and applying some prescriptive rules like integrity or ductility.

Ellingwood [6] proposed a following formula to assess the probability of progressive collapse:

$$P(C) = P(C|DH)\cdot P(D|H)\cdot P(H) \tag{1}$$

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where $P(C)$ is the probability of progressive collapse; $P(H)$ is the probability of the occurrence of a hazard H; $P(D|H)$ is the probability of local damage D as a result of a hazard H; $P(C|DH)$ – the probability of progressive collapse C of structural system as a result of local damage D caused by hazard H.

In [7] there is a good illustration of this expression (1) together with assigned appropriate terms (see Figure 1).

$$P(C)=\overbrace{\underbrace{\overbrace{P(C|DH)}^{\text{robustness}}\cdot\overbrace{P(D|H)}^{\text{element behaviour}}}_{\text{vulnerability}}\cdot\underbrace{\overbrace{P(H)}^{\text{event control}}}_{\text{hazard}}}^{\text{collapse resistance}}$$

maximise

minumise

Fig. 1. Terms in the context of progressive collapse (from [7]).

Considering the above Eq. (1) and Figure 1, the probability of progressive collapse can be minimised in three ways, namely by: controlling abnormal events (term $P(H)$, controlling local element behaviour (term $P(D|H)$) and/or controlling global system behaviour (conventional probability $P(C|DH)$).

It is worth nothing in [7], that controlling abnormal events by structural engineers is normally very difficult, practically impossible. However, engineer can influence the local and global system behaviour, i.e. probabilities $P(D|H)$ and $P(C|DH)$.

Conditional probabilities presented in Eq. (1) can be obtained by a probabilistic risk analysis (PRA), in which it is possible to model uncertainties, study their propagation and the effect on the required performance of the structural systems (with damaged elements). This approach is called structural reliability analysis and failure (collapse in the case in question) is considered achieved when demand E (i.e. the effects generated by the actions) exceeds collapse resistance R. In general case, the probability of failure is equal to:

$$p_f=\int F_R(x)f_E(x)dx \tag{2}$$

where $F_R(x)$ is the CDF (cumulative distribution function) of resistance R and $f_E(x)$ is the PDF (probability density function) of E (effect of actions).

The probability of disproportionate collapse can be defined according to EN1990 [4] as follows:

$$p_f=Prob\left[E\le R\right]\ \text{or}\ p_f=\Phi(-\beta) \tag{3}$$

where β is the reliability index for structural system and $\Phi(\bullet)$ is a normal standard distribution function.

For a correct assessment of disproportionate collapse risk, it may be necessary to consider the presence of multiple hazard events and the initial stage of damage. In this case, Eq. (1) can be generalized as illustrated in the following equation (valid for independent event only):

$$P(C)=P(C|DH)\cdot P(D|H)\cdot\lambda_H \tag{4}$$

where: λ_H can substitute P(H) if occurrence probability is less that 10^{-2}/year. Values of λ_H are reported in [6].

As was shown in [8], if a performance based design approach is adopted, an acceptable value of risk tolerance has to be defined. In the case of a disproportioned collapse, which main consequence is the loss of human life, decision-makers can assume that the performance objective of safeguarding human life is achieved if the following relationship is verified:

$$P(C) \leq p_{tag,h} \quad (5)$$

where $p_{tag,h}$ is the risk threshold defined as “de minimis” which in general case assumed values ranging from 10^{-5}/year and 10^{-7}/year. More detailed discussion presents in our publication [9].

Moreover, in particular case in which so called alternative load path method (ALP-method [6, 10]) is used in design phase, the collapse probability becomes P(C|DH), which in turn has to respect the following equation according to [6]:

$$P(C \mid DH) < \frac{p_{tag,h}}{\lambda_H} \quad (6)$$

Therefore, assuming λ_H equal to 10^{-6}/year..10^{-5}/year, the performance based target probability established by condition (6) requires that the conditional probability of collapse for the modified structural system be in the order of 10^{-2}/year..10^{-1}/year.

Consequently, as shown in [8], the reference reliability index β_0 for the limit collapse state of conditioned by the occurrence of the damage will be in order of 1.5. That is significantly lower than that assumed for ultimate limit state of new buildings for residential and office use in case of ordinary actions (i.e. β_{tag} = 3.8, which corresponds to reference probability for structural system collapse of the order of ~10^{-4}).

Currently, the combinations of accidental actions proposed in the design codes for checking structures in accidental design situations do not take into account that in some cases the accidental effect on the key element may be decisive (i.e., significantly higher than other effects). Therefore, a more objective model of the accidental combination of actions is needed, which will take into account the magnitude of the accidental effect and making it possible to obtain the resistance of the “key element” in accordance with the required reliability class.

2 Load combinations for accidental design situation according to various codes

According to [10, 11], a reliability based approach can be applied to determine reasonable loading combinations for accidental design situation. The actions to be combined reflect the small probability of a joint occurrence of the accidental action and design values of imposed (or live), snow, wind loads.

Hazard events, and mainly, malicious attack are a rare events and many of them suppressed early.

Focussing on the mechanical actions, these are traditionally subdivided into permanent actions and imposed (or variable) action according to [12]. Their variability with time is an aspect of particular relevance for checking of the structural system in accidental design situation. As was shown in [11], in partial factor design method (PFM) for normal conditions, the load variability is considered by a characteristic or design load with a low probability of being exceeded during the service life of the structure. This ensures that the building structure are designed both safety and economically, as in setting the design requirements a balance has been sought between the cost of premature failures and the cost of additional safety investment (see ISO2394 [1]).

Figure 2 shows that reliability indices (failure probabilities) are influenced by the efficiency of safety investments and consequences of failure [1]. The optimal reliability index β^* can be obtained by minimising the sum of investments in safety measures and the accompanying capitalised risk. The target reliability indices derived on the basis of economic optimisation might not be acceptable with regard to requirements concerning human safety, as it is stated in ISO2394 [1]. These reliability indices are denoted as $\beta_{tag,h}$.

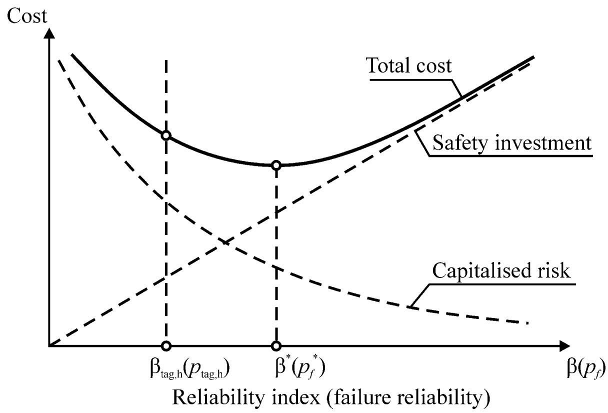

Fig. 2. Principles of cost minimisation, reliability optimum β^* and reliability minimum $\beta_{tag,h}$ according to ISO2394 [1].

It is clear, the day-to-day probability of occurrence of such high (design) load value is low, just as for the day-to-day probability of occurrence of a hazard event (accidental event). Simultaneously taking into account both events would result in very onerous design requirement for accidental design situation (in case of modified structural system robustness checking).

Hence, the reduced partial safety and combination factors in Eurocode [3], ASCE [13] and other codes [14–16] (see Table 1) lesser the required load under consideration for structural design in accidental design situation compared to normal design situation.

Table 1. Accidental action combinations according the various codes.

Standards	**Load combinations**
BS [14]	$D + L/3 + W/3$
Eurocode [3]	$\sum G + P + A_d + \psi_{1,1}Q_{k,1} + \sum \psi_{2,i} Q_{k,i}$ $\sum G + P + A_d + \psi_{2,1}Q_{k,1} + \sum \psi_{2,i} Q_{k,i}$
ASCE 7-05 [13]	$(0.9D$ or $1.2D) + (0.5L$ or $0.2S) + 0.2W_n$ – alternate load path method $1.2D + A_k + (0.5L$ or $0.2S)$ – specific local resistance method $(0.9D$ or $1.2D) + A_k + 0.2W_n$
GSA [15]	$2(D + 0.25L)$ – static analysis $D + 0.25L$ – dynamic analysis
UFC 4-023-03 [16]	$(0.9D$ or $1.2D) + (0.5L$ or $0.2S) + 0.2W_n$ – nonlinear dynamic analysis $2[(0.9D$ or $1.2D) + (0.5L$ or $0.2S) + 0.2W_n]$ – static analysis
D – dead load, L – live load, W – wind load, S – snow load, A – accidental load.	

3 Accidental actions values for "key-element" checking (conditional probability P(D|H))

Recently, many standards [3, 13–16] do not define value for accidental loads, but leave them to the designer. As was noted in [7], after all, the inquiry on the Ronan Point disaster stated that there was only a risk of $3.5\cdot10^{-6}$/year of structural damage due to an urban gas explosion. The pressure due to the gas explosion at Ronan Point was estimated to be between 14 kPa and 83 kPa. Therefore, an accidental pressure of 34 kPa has been adopted by British Standards science 1970. In practice, it is used to determine a notional load applied to key-elements (KE), resulting in more robust construction against gas explosion and other loads as well. However, research [7] has shown, that this pressure may be too high. For example, Ellingwood [6] reports that for a typical residential apartment and venting, the mean maximum pressure generated by a gas explosion is about 17,3 kPa, with standard deviation of 3 kPa. Similary, Ellis and Currie stated that *"for appraisal of structures specially for the event of gas explosion, 17 kPa is considered to be over pressure that will act on all surfaces of the room simultaneously"*. It should be pointed, that this statement is based on housing units, where a maximum pressure of 13 kPa has been measured in gas explosion in single room. But, multi-room, cascading explosions, usually due to piped gas, can produce up to 90 kPa.

The EN1991-1-7 [3] allows a smaller accidental pressure (34 kPa), or value based on calculations that account for room volume, the presence of vents, the strength of windows, and less importantly, the properties of gas mixture. Moreover, the Eurocode [3] defined accidental actions due to the following events: impact from road vehicles; impact from forklift trucks; impact from train; impact from ships and hard landing of helicopters on roofs. According to [3], actions due to impact should be determined by dynamic analysis or represented by an equivalent static force. For buildings, actions due to impact should be taken into account for buildings used car parking; buildings in which vehicles of forklift trucks are permitted, and buildings that are locates adjacent to either road or railway traffic.

4 Load combinations for «key-element» checking in accidental design situation. Results and Discussion

As shown above [11], in general case, hazard events can be classified in two major types: unintentional but identified (Natural and Accidental) hazards and malicious attacks. According to [11], the distinct, nature of two types of hazard implies that the hazard associated uncertainties, severity and frequency of occurrences are significantly different. For unintentional hazards such as earthquake, wind, scour, vessel collision, random stochastic models are typically used to represent the hazard intensity and occurrence. However, for purposely plotted malicious destruction such as explosions and intentional collisions and purposely made accidents (criminal and terrorist attacks), the ordinary random stochastic model is not longer valid.

According to EN1990 [4] and EN1991-1-7 [3] the general format of effects of actions for the accidental design situations is analogous to the general format for STR/GEO ultimate limit states. Here, the loading action is the accidental action, and the most general expression of the design value of the effects of actions is the following:

$$E_d = E\{G_{k,j};\ P_i;\ A_d;\ (\psi_{1,1}\ \text{or}\ \psi_{2,1})Q_{k,i};\ \psi_{2,i}Q_{k,i}\ \} \tag{7}$$

which can also be expressed as:

$$\sum_{j\geq1} G_{k,j}\ "+"\ P"+"\ A_d\ "+"\left(\psi_{1,1}\ \text{or}\ \psi_{2,1}\right)Q_{k,1}\ "+"\sum_{i>1}\psi_{2,i}Q_{k,i} \tag{8}$$

According to background to EN1990 [4], this combination considers that:

– accidents are unintended events such as explosions, fire or vehicular impact, which are of very short duration and have a low probability of accurence;

– a certain amount of damage is generally acceptable in the event of an accident;

– accidents generally occur when structures are in use.

Hence, to provide a realistic accidental combination, accidental actions are applied directly, with the frequent and quasi-permanent combination values used for the main (if any) and other variable actions respectively (see cl. 6.4.3.3 (3) EN1990 [4]).

Regarding the representative value (frequent and quasi-permanent) of a possible main variable action, EN1990 [4] states that discretion is left to national authorities for the reason that all accidental situations or events cannot be similarly treated. When the main variable action is not obvious, each variable action should be considered in turn as the main action.

The combination for accidental design situation either involve an explicit design value of accidental action A_d (e.g. impact) or refer to a situation after an accidental event ($A_d = 0$).

The partial factors for actions for ultimate limit states in the accidental design situations are normally taken equal to 1.0, in general, not only are the reliability elements for actions modified for the partial factors for resistances.

Based on results of our own investigations [17], we proposed to use for checking of the "key-element" resistance the following combination of actions for accidental design situation (combination comprises accidental action $A_d \neq 0$):

$$E_{d,A} = \sum_{j=1}^{n} \left(\gamma_{GA,j}\right) G_{k,j} \text{"+"} A_d \text{"+"} \psi_{A,1} Q_{k,1} \tag{9}$$

where $G_{k,j}$ is the characteristic value of a permanent action "j";

$Q_{k,1}$ is the characteristic value of the leading variable action;

A_d is the design value of the accidental action;

$\gamma_{GA,j}$ is the combination factor applied to a permanent action "j";

$\psi_{A,1}$ is the combination factor applied to the leading variable action according to Table 2.

In Table 2 we relate values of the combination factors ψ_A with required reliability class RC for structural element and factor k, which is determined as ratio:

$$k = \frac{A_d}{E_k} \tag{10}$$

with

$$E_k = \sum_{j=1}^{n} G_{k,j} + Q_{k,1} + \sum_{i>1} Q_{k,i} \tag{11}$$

where $Q_{k,i}$ is the characteristic value of the accompanying variable actions.

Proposed combination of actions for accidental design situation Eq. (9) gives resistance of the "key-element" in accordance with required reliability class. It was found that the application of the ψ_A coefficients to the accompanying (non-dominant) loads does not lead to a change in the reliability indices. Because of the significant accidental action A, the influence of all other loads decreases. Only the leading variable action have noticeable influence on the reliability indices. In this regard in Eq. (9), only dominant variable loads are taken into account in combination of actions for accidental design situation for the "key" system elements. For non-dominant variable action $\psi_{A,i,2} = 0$.

Table 2. Combination factors ψ_A and partial factors γ_{GA} for checking of the "key-element" resistance.

Reliability Class	k_A	Values of the coefficient for variable actions			
		Imposed (Q), $\psi_{A,Q}$	**Wind (W), $\psi_{A,W}$**	**Snow (S), $\psi_{A,S}$**	**Permanent (G), ψ_{GA}**
RC2	1.0	0.8	0.8	0.7	1.0
	1.5	0.6	0.6	0.55	
	2.0	0.5	0.5	0.4	
	2.5	0.35	0.4	0.3	
	3.0	0.2	0.3	0.2	
	3.5	0.1	0.2	0.1	
	4.0	0.05	0.15	0.05	
RC3	1.0	1.0	1.05	1.0	1.05
	1.5	0.9	0.95	0.85	
	2.0	0.8	0.8	0.7	
	2.5	0.7	0.7	0.6	
	3.0	0.55	0.6	0.5	
	3.5	0.45	0.5	0.4	
	4.0	0.4	0.45	0.35	

Conclusion

In the paper was considered accidental action combinations and values of identified accidental loads according the various codes. The combination of actions for accidental design situation for checking of the "key-element" resistance was proposed. The calibrated values of the combination factors $\psi_{A,i,1}$ for the key elements (see Table 2) depend on the required reliability class of structural elements and the factor k, which is defined as the ratio of the design value of the effect from the accidental action A_d on the element and the effect E_k from the total characteristic load on this element. This approach provides a more objective assessment of the resistance of the "key-element".

Depending on the magnitude of the accidental action, the values of the combination factors $\psi_{A,i,1}$ are for the imposed load from 0.05 to 1.0, for the wind load from 0.15 to 1.05, for the snow load from 0.05 to 1.0.

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